STUDY OF GROUND-BASED AND SPACE VEHICLE INFRARED INSTRUMENTATION FOR THERMAL PHOTOGRAPHY OF THE MOON AND PLANETS, INCLUDING EXPERIMENTAL PROGRAMS AT SELECTED OBSERVATORIES

by

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FINAL REPORT

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ABSTRACT

This is the Final Report of a project for the measurement of exact and precisely localized brightness temperatures of the moon at various phases and at infrared wavelengths. The main activities of the project, summarized by the Abstracts of Scientific Reports issued during the lifetime of the project, include development of specialized instrumentation, preliminary reduction of observations, development of theoretical models of the lunar surface, and development of a computer program for automatic reduction of the observational material. The grant expired before any substantial reduction of data could be completed.

I. INTRODUCTION

The project, of which this is the Final Report, was initiated with the aim of obtaining exact infrared brightness-temperatures at precisely identified locations on the moon at various phases.

The first major task of the project was the development of suitable instrumentation for making the observations. The instrumentation developed under this grant has been described in Scientific Reports No. 1, 2, 3, 10, and the unnumbered "Radiation Pyrometer" report, the Abstracts of which appear in Part IV below. The instrument designed for this purpose included a photographic system which recorded the precise points under observation. In this way small fluctuations of brightness with time could be studied for different types of physical surface. The "Radiation Pyrometer" Report is essentially the Final Report on instrumental development.

Scientific Reports No. 5, 6, 7, and 8 present the results of a preliminary analysis of some of the observations; Nos. 7 and 8 are concerned with the development of theoretical models for use in further interpretation of the observations.

Considerable effort was expended in the later years of the project on the development of a computer program for automatic reduction of the observations, with the results detailed in Scientific Report No. 9 and 9A. The program was tested on one day's observations and appears to work satisfactorily. (One copy of the IBM printout for this day, 29 October 1966, accompanies this report, as Part III).

Unfortunately the grant expired before further analysis or reduction of the observational material could be carried out. A summary of the present status of this material, prepared by Mrs. Lillian Woo, makes up Part II of this report.

II. REPORT OF DATA PROCESSING OF LUNAR INFRARED MEASUREMENTS

Since January 1964, a total of 2407 scans and 12,765 pictures have been reduced from 70 nights of observations. A complete listing of these data appears on the following pages. There are 1.5 million points of information, which have been digitized onto approximately 250,000 IBM data cards. Data related to this project, complete, partially reduced, or raw, include:

1. Two IBM magnetic tapes, duplicate, 29 October 1966
2. Two sets of output printout
3. Two sets, source program listing
4. Two decks, source program cards
5. Two decks, source program in binary cards
6. One set, Mylar mapping
7. Two sets, Lunar scans mapping reduced paper form
8. 250,000 data cards, in 73 drawers
9. 120 rolls of Sanborn tape
10. About 200 cans of film, both negatives and positives
11. 70 magnetic recording tapes
12. Filter Curves file
13. All Ephemeris cards, wide filter cards, precipitable cards, K cards, etc.

The system for processing the lunar infrared measurements is described in Scientific Report No. 9; a revision to the LUNAR program, by Mr. John B. Newell of the Harvard Computing Center, was completed in 1968, and appears as Scientific Report No. 9A.

We have processed the observations for 29 October 1966, with 75 scans which produced 37,443 data points of information. The printout, in one copy, is submitted with this Report.

LISTINGS OF LUNAR DATA REDUCTION

OBSERVATION DATE	LUNAR DATE	NO.OF SCANS	NO. OF PICTURE	PICTURES IDENTI-FIED	PIC.CARDS PUNCHED	K CARDS CALCULATED	FILTER ASSIGNED
6312-30 *	no data						
6401-30 *	no data						
6402-27 *	no data						
6406-24	14	153	411	mostly	no	no	no
6411-15	11	22	96	done	no	no	no
6412-15	11	44	222	done	no	no	no
6412-16	12	148	700	done	no	no	no
6412-18(Eclipse)	14	77	498	done	no	no	no
6503-20	no data						
6503-17	14	4	58	done	no	nc	no
6504-06 *	no data						
6504-07 *	no data						
6504-10	8	33	140	done	no	no	no
6504-11	9	57	244	done	no	no	no
6504-15	13	39	211	done	no	no	no
6505-05	4	22	78	done	no	no	no
6505-06	5	13	134	done	no	no	no
6505-12	11	3	23	done	no	no	no
6505-13	12	35	382	done	done	no	no
6505-14	13	8	68	done	done	no	no
6505-15	14	44	261	done	done	no	no
6505-18	17	37	198	done	done	no	no
6505-24	23	53	240	done	done	no	no
6506-05	5	14	73	done	done	done	Curve #11
6506-11	11	19	120	done	done	done	" # 11
6506-12	12	22	120	done	done	done	" # 11
6510-06	11	12	113	done	done	done	" # 11
6510-07*	12						
6609-07* *	22						
6609-08	23	13	111	done	done	done	" # 12
6610-03	18	41	223	done	done	done	" # 12
6610-04	19	39	234	done	done	done	" # 12

OBSERVATION DATE	LUNAR DATE	NO.OF SCANS	NO. OF PICTURE	PICTURES IDENTI-FIED	PIC.CARDS PUNCHED	K CARDS CALCULATED	FILTER ASSIGNED
6610-06	21	62	286	done	done	done	Curve #12
6610-07*	22						
6610-27	13	55	340	done	done	done	" # 12
6610-28	14	62	499	done	done	done	" # 12
6610-29	15	75	423	done	done	done	" # 12
6610-30	16	89	456	done	done	no	no
6610-31	17	35	189	done	done	no	no
6611-04	21	94	470	done	done	no	no
6611-05	22	67	350	done	done	no	no
6701-16*	6		154				
6601-18	8	96	482	done	done	no	no
6701-21	10	8	56	done	done	no	no
6702-17	8	37	227	done	done	no	no
6703-19*	8		286				
6703-19/20	9	73	478	done	done	no	no
6703-21	10	91	571	done	done	no	no
6705-17	7	33	219	done	done	no	no
6705-18	8	11	70	done	done	no	no
6706-01(dayfilm)	23	33	170	done	done	no	no
6706-01*	23						
6709-19	15	27	172	done	done	no	no
6709-20	16	9	99	done	done	no	no
6709-21*	17		97				
6710-21	17	9	88	done	done	no	no
6710-22	18	36	290	done	done	no	no
6710-23	19	55	438	done	done	no	no
6710-24	20	68	498	done	done	no	no
6711-17	15	7	104	done	done	no	no
6711-20	18	46	346	done	done	done	Curve #13
6711-21	19	46	468	done	done	no	no
6712-14 *	12	39	350	no*	no	no	no
6712-15 *	13	29	168	no*	no	no	no
6712-16 *	14	12	133	no*	no	no	no
6712-17 **	15	35	333	no	no	no	no
6712-21 **	20	71*	565	no	no	no	no

OBSERVATION DATE	LUNAR DATE	NO.OF SCANS	NO. OF PICTURE	PICTURES IDENTI-FIED	PIC.CARDS PUNCHED	K CARDS CALCULATED	FILTER ASSIGNED
6802-04/5**	6	39**	164	no	no	no	no
6802-05/6	7	72	555	done	done	done	Curve#13
6802-06/7**	8	82**	659	no	no	no	no
TOTAL		2,555	16,211				

94% of scans were measured and 79% of pictures were done.

NOTE: Curve # 11 = Filter #3 of Dec. 1965

Curve # 12 = Filter #3 of Sept. 1966

Curve # 13 = Filter #3 of Feb. 1968(Filter was not assigned, but I did it by logic thinking)

Data with * were not reduced on account of either bad film or different sanborn tape, which is impossible to measure.

Data with ** were not reduced on account of short of time and workers, so picked the best among those closer observations.

* in the column of "No.of scans" means measurements were not completed.

III. EPHEMERIS AND TEMPERATURE DATA OF LUNAR SURFACE OF 29 OCTOBER (the 15th Lunar Day) 1966.

IBM printout, included in one copy only

The material in this printout exists also on magnetic tape. As discussed on p. 11 of Scientific Report No. 9, it was hoped eventually to present this material graphically by plots of brightness temperature on a lunar orthographic framework. Unfortunately the grant expired and funds were exhausted before this objective could be achieved.

IV. Scientific Reports Issued on NASA NsG 64-60

Scientific Report No. 1
Study of Infrared Instrumentation for Thermal Photography of the Moon
Hector C. Ingrao, Donald H. Menzel and J. Anthony Burke
May 15, 1961

Successful thermal photography, for the primary purpose of temperature measurement, depends on the value of the signal intensity at the ground, or in a balloon or space vehicle. Computations predict the image temperature, for an image-forming system with a single thermal detector having a sequential read-in and read-out.

Thermal detectors and available single-quantum detectors with responses at wave lengths of approximately 5μ and longer are intercompared in terms of figures of merit.

Infrared sensitive image-forming systems are surveyed and discussed for lunar thermal photography. Lateral heat conduction in the target plate of a simultaneous read-in image-forming system is analyzed to determine the size of the minimum resolvable element. On the basis of this analysis, we will investigate the possible utility of new thermal detectors as target plates for image-forming systems of simultaneous read-in.

Scientific Report No. 2
Instrumentation for Observations of Planets in the Far Infrared
Hector C. Ingrao and Donald H. Menzel
June 15, 1963

Characteristics of various infrared detectors are analyzed and tabulated. The development of a series of ferroelectric bolometers and a radiation pyrometer is discussed.

Scientific Report No. 3
Ferroelectric Bolometer for Space Research
Hector C. Ingrao, Frederic J. Kahn, and Donald H. Menzel
November 1, 1963

In this report we compare the ferroelectric bolometer with other thermal detectors for use in space instrumentation.

We manufactured ceramic ferroelectric bolometers with Curie points between -10°C and +10°C and dimensions as low as

.5 mm x .5 mm x 50 microns. We measured the performance of a radiation pyrometer with a ferroelectric bolometer 1.0 mm x 1.0 mm x 0.2 mm. With an incident infrared signal of 5.8 x 10^{-9} watts peak-to-peak, chopped at 2.5 cps, and a bandpass $\Delta f = 0.25$ cps, at room temperature, the noise level of the system is 4.2 x 10^{-10} watts rms. Theoretical analyses of the responsivity and minimum detectable power are presented. Work sponsored by the National Aeronautics and Space Administration.

Scientific Report No. 4 (not issued)

Scientific Report No. 5
Isotherms in the Region of Proclus at a Phase Angle of 9.8 Degrees
Andrew T. Young and Harold Boeschenstein, Jr.
September 15, 1964

An isothermal map of the Proclus area of the Moon and a description of the method used for making the map are presented. Correlation between the isotherms and the visual features is also given.

Scientific Report No. 6
A Critical Analysis of Lunar Temperature Measurements in the Infrared
Hector C. Ingrao, Andrew T. Young, and Jeffrey L. Linsky
April 15, 1965

The Harvard College Observatory radiation pyrometer for lunar measurements and the associated data reduction techniques are described. Under good observing conditions, this system can measure the brightness temperature of a square area of 12 x 12 kilometers at the sub-earth point of the lunar surface, located with an accuracy of $\pm$ 2 km; relative temperatures near the subsolar point can be measured with a precision of $\pm$ 1°K and an absolute accuracy of $\pm$ 8.5°K, and lower temperatures can be measured accurately down to about 180°K with a post-detection integration time of 0.2 seconds. Below this temperature, the integration time has to be increased since the instrumental noise starts contributing significantly to the uncertainty of temperature measurements. Some data obtained at the total lunar eclipse on June 24-25 and December 18-19, 1964 are presented.

Propagation of error analysis shows that it would be very difficult to determine the subsolar point temperature with an absolute accuracy better than ±5°K, or a few degrees during eclipse. Numerical integration of the heat-flow equation for several lunar surface models shows that the accuracy of infrared brightness temperature measurements during an eclipse is too low to permit realistically more than the most general conclusions about the lunar surface. In the two-layer model thicknesses greater than about 4 mm cannot be measured by infrared technique.

1) The eclipse observations cannot be reconciled with a model having homogeneous surface material with temperature-independent thermal properties.

2) Eclipse observations of the crater Tycho and its environs are consistent with models having two-layer temperature-independent thermal properties.

3) Very different models can have similar surface temperatures during an eclipse, but which differ by 10°K or more at depths of several millimeters. The combination of millimeter-wave data with infrared data may possibly distinguish one model from another.

Homogeneous models with linearly temperature-dependent thermal properties and models including a radiative transfer term give a better fit with the lunation data of Murray and Wildey.

Since the eclipse and lunation data may both be described by several different models of the thermal properties of the lunar surface, at present the possibility of our learning about these properties from infrared data alone seems very doubtful.

A general computer program coded in the FORTRAN language has been written which solves the heat conductivity equation for a multilayer lunar surface and for arbitrarily temperature-dependent thermal properties (Scientific Report #7).

Scientific Report No. 7
A Computer Program to Solve the Heat-Conduction Equation in the Lunar Surface for Temperature-Dependent Thermal Properties
Jeffrey L. Linsky
July 15, 1965

A computer program is presented to solve the heat conduction equation for boundary conditions appropriate to the lunar surface during an eclipse and during a lunation. This program allows for very general representations of the temperature- and depth-dependent thermal properties in a multi-layer model. Both infrared and microwave brightness temperatures may be predicted for the Moon and similar rotating bodies in which thermal conduction and radiative transfer are the most significant forms of energy transport near the surface.

Scientific Report No. 8
Models of the Lunar Surface Including Temperature-Dependent Thermal Properties
Jeffrey L. Linsky
January 15, 1966

The thermal conditions in the lunar surface are considered on a gross scale in terms of models with temperature-dependent thermal properties, including radiative energy transport. Agreement is obtained with infrared measurements of cold terminator temperatures and radio lunation data at millimeter wavelengths for a range of postulated parameters of the surface material. The observed increase of mean radio brightness temperature with wavelength is interpreted as due to radiative energy transport and the resultant nonlinearity of the heat-conduction equation, rather than to a large radioactive heat flux.

The postulated existence of radiative energy transport is consistent with a porous or frothy medium, in agreement with photometric and laboratory simulation experiments, as well as with recent radar depolarization measurements. A distance scale of 0.1-0.3 mm for the effective mean separation of radiating surfaces is suggested by this interpretation of the data.

Scientific Report No. 9
Data Processing of Lunar Infrared Measurements at High Spatial and Radiometric Resolution to Obtain Brightness Temperatures
Hector C. Ingrao, Andrew T. Young, Harold Boeschenstein, Jr., Yung C. Hu, Elgie C. Levin, Mary F. C. Leyland, Jeffrey L. Linsky, and John B. Newell
June 1, 1966

A unique data processing of lunar infrared measurements at high spatial and radiometric resolution to obtain brightness temperature is presented. This system takes into account all the instrumental parameters and observing conditions, including amount of ozone, carbon dioxide, and precipitable water along the path. Possible drifts in the instrument or changes in the sky emittance are also handled by the system. Moreover, for each line of scan the accuracy in the location of the resolution element on the lunar disk is also given, taking into account systematic errors such as the differential atmospheric refraction between visible and infrared rays.

The programming used in the data processing package produces a compact simplified data file oriented towards ease of retrieval of various forms (i.e., plotting of different subsets of the data). The techniques used to obtain this data file depend on a high degree of separation of different phases of the data-reduction. This separation is reflected in the organization of the program as a very simple supervisory program with many subroutines, each performing highly specific calculations.

Scientific Report No. 9A
Emendations to Scientific Report No. 9, and Final Documentation of the LUNAR Program
John B. Newell
April 1, 1969

This report is not a complete and independent document. It is intended for use only as a supplement to Scientific Report No. 9, "Data processing of lunar infrared measurements at high spatial and radiometric resolution to obtain brightness temperatures" by H. C. Ingrao et al., issued in June 1966.

Part 1 summarizes the computer-program debugging activity, and Part 2 lists a number of specific emendations that should be made to p. 9-45 of Scientific Report No. 9. Part 3 is a complete printout of the emended data-processing program and should replace p. 47-87 of Scientific Report No. 9.

Scientific Report No. 10
Lunar Brightness Temperature Measurements
Hector C. Ingrao
June 1, 1967

The instrumental parameters, i.e., spectral transmittance of the filter, relative spectral transmittance of the immersion lens (thermistor bolometer), radiant emissivity of the calibration and reference blackbodies, size of the resolution element, effective f-number, and reflectivity of the telescope mirrors, as used in the reduction of our lunar brightness temperature measurements, are discussed. Scientific Report No. 9 under NASA Research Grant No. NsG 64-60 described the processing of the raw data, and Scientific Reports No. 4 and No. 6 under the same grant described the techniques and instrumentation used for the measurements.

The assumptions about the properties of the lunar surface used in the reduction of our measurements are also discussed. Equations and tables are presented so that, when more reliable data about these assumptions, i.e., lunar emissivities, directional properties of the lunar surface, subsolar point temperatures, and atmospheric transmittance, are available, the temperature brightness given in our printouts (blackbody temperatures) may be corrected to obtain actual surface temperatures.

Scientific Report (unnumbered)
Radiation Pyrometer for Lunar Observation
Hector C. Ingrao and Donald H. Menzel
April 1, 1969

This report analyzes a radiation pyrometer for lunar observations, developed at the Harvard College Observatory.

One of the criteria for designing this pyrometer was the utilization of thermal detectors for developing techniques suitable for space instrumentation, and to make observations possible outside the United States. Moreover, the astrometric aspects of the radiometric measurements in this radiation pyrometer were seriously considered.

The pyrometer has three channels: infrared, photographic (astrometric purposes), and visual. All three channels use the same telescope optics and are commutated by a two-sided mirror chopper. The pyrometer head has plug-in units, making possible the use of different thermal detectors, photomultiplier tubes, and a focusing test unit.

The location of the resolution element on the lunar surface could be achieved within three seconds of arc, or one-third of the resolution element. The noise level of the pyrometer, under certain conditions, is 6×10^{-11} watts peak-to-peak for one second post-detection integration time.

Detailed descriptions of the electro-mechanical parts of the radiation pyrometer and its electronic circuitry are given, since a great deal of effort was put into the design of these parts.

Technical Report

Prepared for Arthur D. Little, Inc., Cambridge, Mass., and
NASA NsG 64-60
A Study of Thermal Response of the Lunar Surface at the Landing Site During the Descent of the Lunar Excursion Module (LEM)
Jerome T. Holland and Hector C. Ingrao
April 1, 1966

This report analyzes the thermal response of the lunar surface at the landing site due to the radiative and convective heat transfer from the LEM exhaust nozzle. A computer program has been written to analyze the thermal transients as a function of 1) the thermal model of the lunar surface materials; 2) depth beneath the lunar surface; 3) distance from the touchdown point. The physical meaning of the answers obtained in our analysis depends on how accurate the heat transfer parameters are for the assumed model, during the LEM descent. Therefore we prefer to stress the method of analysis rather than the numerical conclusions.